Vector Fields Simplification – A Case Study of Visualizing Climate Modeling and Simulation Data Sets

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ABSTRACT

In our study of regional climate modeling and simulation, we frequently encounter vector fields that are crowded with large numbers of critical points. A critical point in a flow is where the vector field vanishes. While these critical points accurately reflect the topology of the vector fields, in our study only a subset of them is worth further investigation. We present a filtering technique based on the vorticity of the vector fields to eliminate the less interesting and sometimes sporadic critical points in a multiresolution fashion. The neighboring regions of the preserved features, which are characterized by strong shear and circulation, are potential locations of weather instability. We apply our feature-filtering technique to a regional climate modeling data set covering East Asia in the summer of 1991.

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1 INTRODUCTION

In climate modeling and simulation, wind velocity plays a critical role in characterizing a region's weather. Wind velocity is the only vector field dimension in an otherwise all scalar field – including temperature and pressure – multidimensional climate data set. The content of our climate data sets [4], whether scalar or vector fields, is intentionally stratified in 2D layers that are individually characterized by different atmospheric pressure from 25 to 995 mbar levels. For visualization of the overall field topology, we stack up all the 2D layers of field data and build a 3D data volume. While this stacking strategy has certain deficiencies when studying three dimensional flow fields, the primary concern of this study was to find a way to simplify a vector field visualization that is crowded with large numbers of critical points. A critical point in a flow is where the vector field vanishes. In our discussion, we use the terminology introduced by Helman and Hesselink [1] in their pioneering work of visualizing vector field topology.

Figure 1 shows a 3D volume filled with 442 critical points encoded in different intensities according to their types. These critical points are computed from the wind-velocity dimension during a calm day of a 92-day climate simulation. Clearly the figure is so busy that we can no longer include any other information for visualization and analysis. Our goal, therefore, is to eliminate the critical points that have less impact on the weather condition and preserve only the significant ones for further study.

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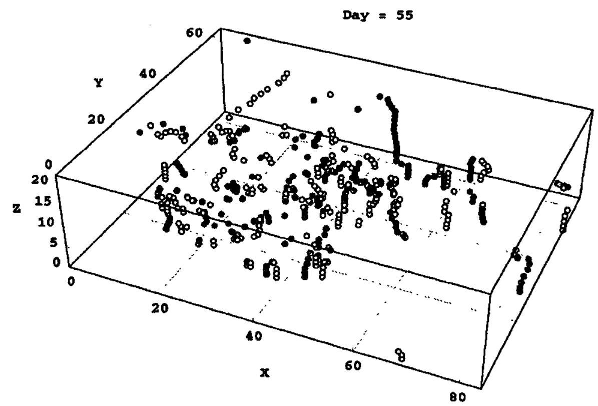

Figure 1: The 442 critical points are shaded according to their types. They are computed from the wind-velocity dimension during a calm day of a 92-day simulation. There are 224 white saddles, 118 black source (both node and focus) points, and 100 gray sink (both node and focus) points.

This feature-filtering work is a part of our ongoing effort to develop data signatures for very large scientific data sets [7]. A data signature is a mathematical data vector that captures the essence of a large data set in a small fraction of its original size. It is used to conduct analysis at a higher level of abstraction and yet still reflect the intended results as if using the original. Our filtering scheme eliminates the noisy information caused by less important features in a vector field and further improves the compactness of the signature vectors.

2 RELATED WORK

Several recently developed techniques [2][3][5] are designed to simplify a busy vector field topology. They are generally classified into either explicit or implicit methods [2]. The basic characteristic of an *explicit* technique is to first generate the topology from a flow field data set and then simplify the topology by eliminating some of the flow features. On the other hand, an *implicit* method smoothes out sharp and local changes of a field before its topology is generated.

De Leeuw and van Liere [3] have developed a classic approach to collapse flow topology using area metrics. The basic concept of this explicit approach is to reduce feature sets such as (node, saddle, node) along the flow lines into a single node recursively, after the critical points (sinks, sources, saddles), flow boundaries lines, and in-/out-flow boundary regions are identified.

Another elegant technique developed by de Leeuw and van Liere [2] is to collapse flow topology according to the pairwise distances between two critical points. It builds on the assumption that removing a nearby pair does not drastically change the global structure of a topology. The same paper also presents an implicit method that uses a low-pass filter to smooth out the data and thus eliminate some of the potential critical points.

Telea and van Wijk [5] present an innovative and very different technique to simplify a flow topology based on iconography. Full sized hedgehog-like arrow icons with different shapes and lengths are used to represent clusters of neighboring vectors that have similar shapes. The resultant visualization is extremely descriptive and easy to understand.

All the techniques we have described so far attempt to simplify the entire vector field. Conversely, our approach emphasizes keeping full details within certain closed boundaries and eliminating the rest. By adjusting the boundary thresholds, we achieve a multiresolution filtering system.

3 REGIONAL CLIMATE SIMULATION

The multidimensional time-varying climate modeling data set [4] used in this paper has all the basic characteristics and features to demonstrate our concept. The data set has five data dimensions (pressure, temperature, water-vapor mixing ratio, and two wind-velocity components) of different types (scalar and vector fields) and spatial dimensions (2D and 3D) recorded daily during a 92-day period. Each of these variables contains more than 127,000 real numbers. They add up to more than half a million numbers per time step and over 233 megabytes of data in the modeling data set. The climate data set is a simulation of the extreme flood conditions of Eastern Asia (China and Japan) from May to July 1991. During that period, the weather was characterized by three rainfall episodes. The first episode was between May 18 and 26, the second between June 2 and 16, and the last between June 30 and July 13. Together, the three episodes of the unusually early and long rainy season clearly separate the summer into seven periods.

3.1 Multiresolution Feature Filtering

Our primary goal is to adaptively eliminate field features that have little impact on the overall weather condition of the region. In other words, we emphasize critical points in certain closed boundaries and pay no attention to the ones outside these areas. In the context of vector calculus of fields, we are looking for flow boundaries that are characterized by strong shear or circulation. These vortex features are known indicators of potentially unstable weather conditions such as wind, clouds, rainfall, or even typhoons. By only focusing on the flow information associated with the critical points within these boundaries, we provide a much clearer and less cluttered visualization to study the field topology and the corresponding weather conditions.

3.2 Vorticity-Based Filter

The first step to build our feature filter is to find the curl of the entire vector field using the following equation:

$$curl\ \vec{v} = \nabla \times \vec{v} = \frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}$$

The result is a vorticity scalar field that describes the shear and circulation characteristics of the original vector field. The magnitudes of these scalar fields provide a basis for us to control the boundary thresholds as well as the number of critical points we want to include in our analysis.

3.3 Example

Figure 2 shows a 2D vector field generated from the 945 mbar level of the wind velocity dimension during the 86th day of the simulation. (See Figure caption for a detailed description.) The absolute magnitudes of the vorticity scalar fields are mapped to a segmented grayscale contour map in the background with the high value mapped to the white end. By progressively eliminating critical points in each contour level (from black to white), we achieve a multiresolution feature-filtering system for our climate study.

The display in Figure 2 is so saturated with information that we can no longer show the boundaries and regions of the vector field. We have to put this information in a second display, as shown in Figure 3. This time we replace the segmented contour map with a continuous gray scale map to reflect the actual vorticity strength and add flow boundary lines to show flow regions.

3.4 Discussion

The fact that we need two figures (Figures 2 and 3) to show all the important features of a 2D vector field is by itself a good argument to apply the feature filter to simplify the visualization.

At least five major circulation features in various locations are shown in Figure 3. They can be spotted by the swirl formed by the line hedgehogs, the black/white spiral boundary lines, or the high-vorticity areas shown in white. However, it is the segmented contour map on the strength of vorticity in Figure 2 that brings out the shape of a typhoon § in a closed boundary surrounding critical point #4. We argue that our feature filter helps isolate features of special interest and significance in a vector flow field.

Of the five major swirls shown in Figure 3, four of them have the stream path – shown by black/white boundary lines – stop at the critical points. The black boundary line surrounding critical point #4, however, reaches a stable orbit not far from the sink point and stops. This orbit is similar to a *stable limit cycle* [6] that separates the external high-velocity circulation from the tranquil region at the center – a strong indication of a summer typhoon or hurricane in the Asia/Pacific area. This supports our argument that some features are more important than others and that we can make meaningful observations and interpretations without considering every piece of information available in the field.

Conventional wisdom would have us select a feature filter based on the magnitude of the wind-velocity vector instead of the vorticity to highlight the weather instability of a field. But what this study shows is that the vorticity is a much better metric for the job. We would have missed the center of a typhoon with a vector-magnitude-based filter.

4 MULTIRESOLUTION VISUALIZATION

In this example, we stack up multiple layers of 2D vector fields using the same data set from Figures 2 and 3 to form a volume for feature simplification. Color Plate 1 shows the original volume with all critical points followed by the filtered versions with threshold relative vorticity magnitudes of 3, 4, 6, 8, and 10. The x- and y-axes show the coordinates of the data grid points. The z-axis shows the atmospheric pressure levels from 25 to 995 mbar. The black contour lines show the threshold vorticity boundaries of the corresponding layers. We include two sample

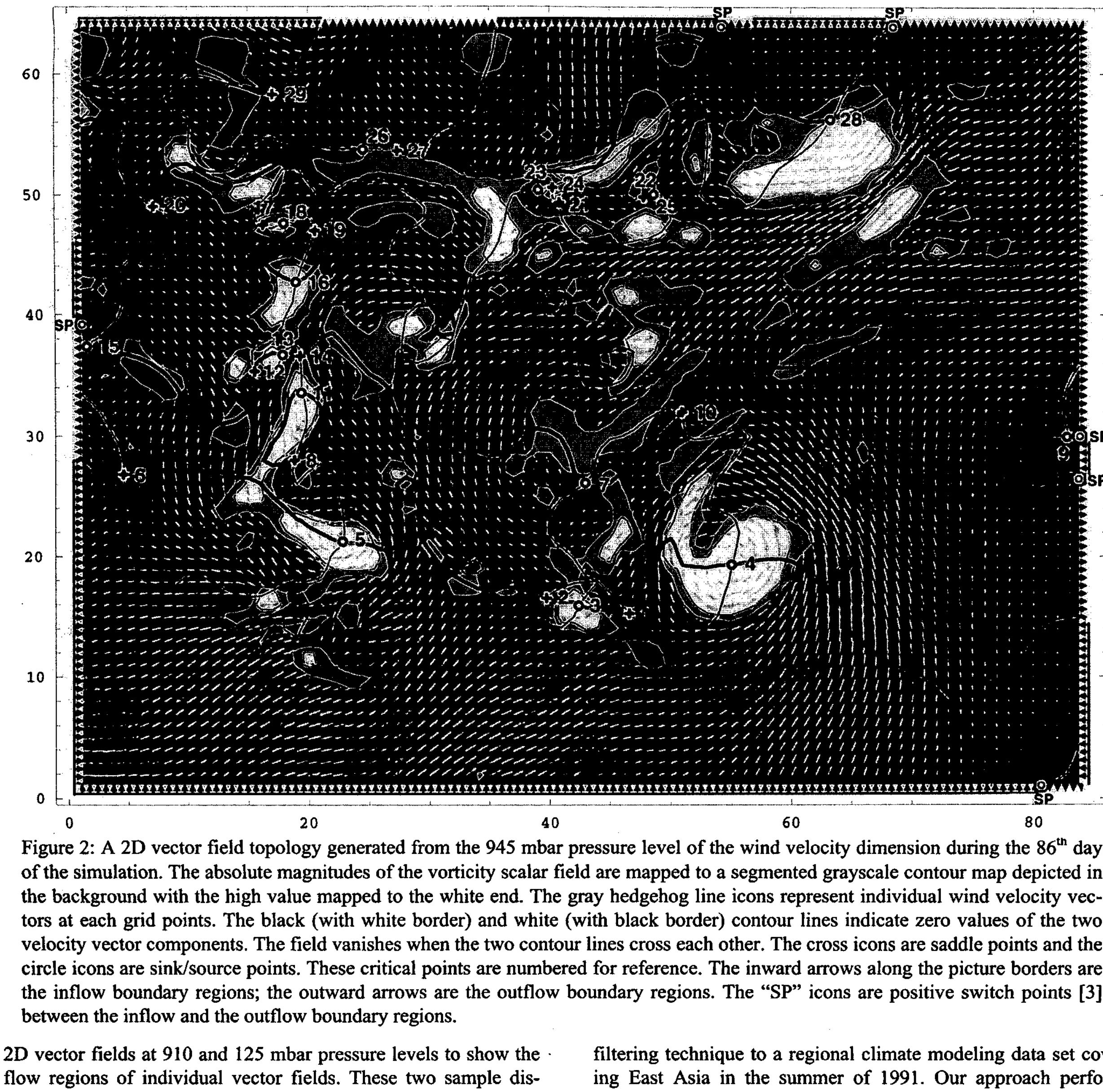

Figure 2: A 2D vector field topology generated from the 945 mbar pressure level of the wind velocity dimension during the 86th day of the simulation. The absolute magnitudes of the vorticity scalar field are mapped to a segmented grayscale contour map depicted in the background with the high value mapped to the white end. The gray hedgehog line icons represent individual wind velocity vectors at each grid points. The black (with white border) and white (with black border) contour lines indicate zero values of the two velocity vector components. The field vanishes when the two contour lines cross each other. The cross icons are saddle points and the circle icons are sink/source points. These critical points are numbered for reference. The inward arrows along the picture borders are the inflow boundary regions; the outward arrows are the outflow boundary regions. The "SP" icons are positive switch points [3] between the inflow and the outflow boundary regions.

2D vector fields at 910 and 125 mbar pressure levels to show the flow regions of individual vector fields. These two sample displays serve as data probes to study the flow directions of the fields as well as the boundary regions of individual layers. To further simplify our figures, we group the critical points into saddle (blue cross) and non-saddle (yellow cube) classes. We observe that the critical points in the original data volume gradually disappear as the threshold value (shown by black contours) increases. The critical points inside the typhoon vortex are among the strongest flow features to stay in the volume until the end.

5 CONCLUSION AND FUTURE WORK

We present a filtering scheme based on the vorticity of the vector fields to eliminate the less interesting and sometimes sporadic critical points in a multiresolution fashion. We apply our feature-filtering technique to a regional climate modeling data set covering East Asia in the summer of 1991. Our approach performs reasonably well in studying the instability conditions of climate modeling and simulations.

We are in the process of integrating this technique into our scientific data signature work [7] to further improve the compactness of the signature vectors. We also want to define a practical metric system to estimate the error introduced by the feature elimination. Eventually we want to generalize this approach for other applications such as combustion simulations.

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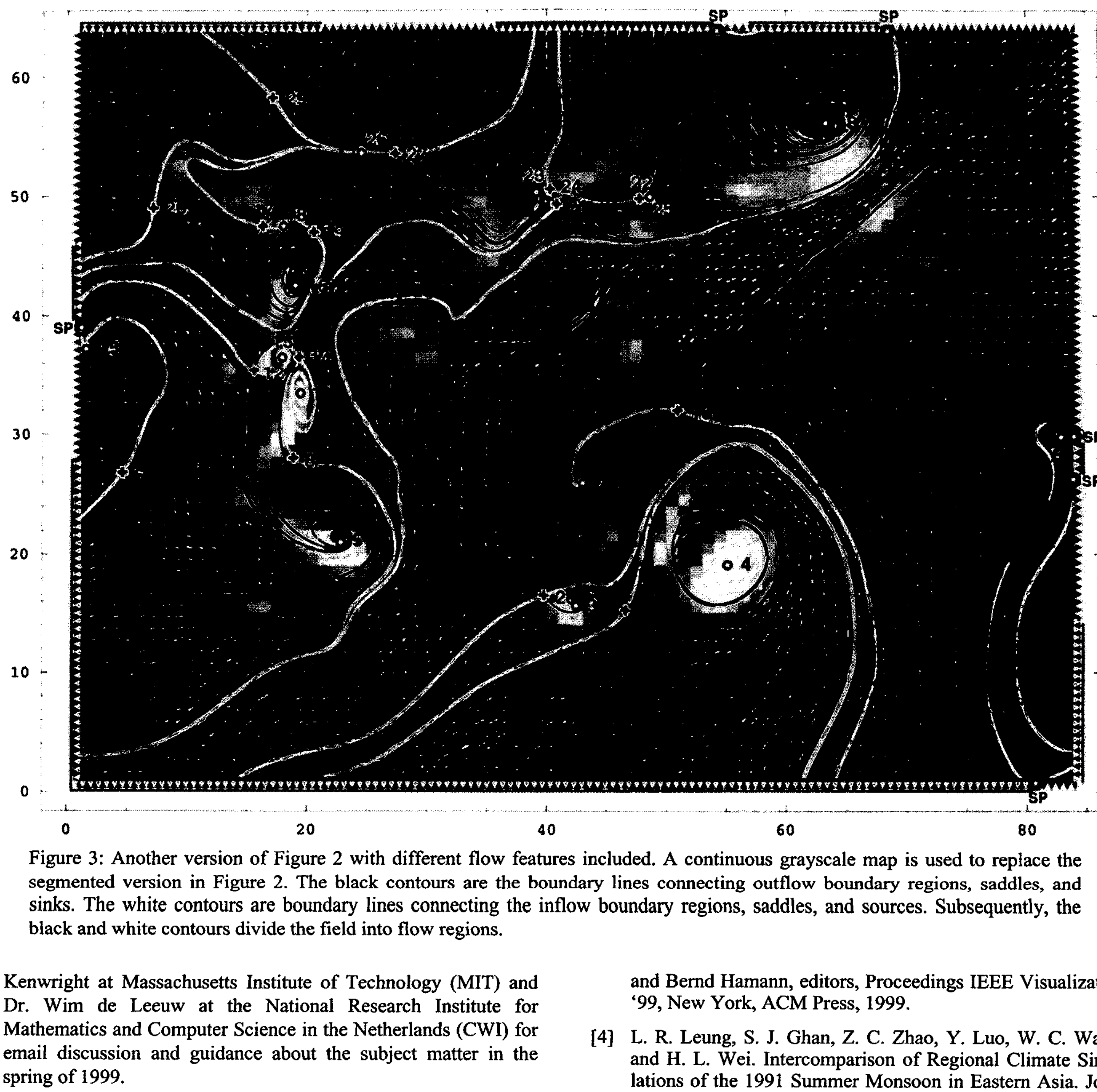

Figure 3: Another version of Figure 2 with different flow features included. A continuous grayscale map is used to replace the segmented version in Figure 2. The black contours are the boundary lines connecting outflow boundary regions, saddles, and sinks. The white contours are boundary lines connecting the inflow boundary regions, saddles, and sources. Subsequently, the black and white contours divide the field into flow regions.

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